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14. ABSTRACT
This report describes the technical progress towards the development of signed processing algorithms for hybrid lidar- radar designed to improve detection performance.

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MEMORANDUM

Subject: Annual Report
ULI: FY2014

This document provides a annual report on the project "Advanced Digital Signal Processing" covering FY2014.

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Award Information

Award Number	N000141110371
Title of Research	Advanced Digital Signal Processing for Hybrid Lidar
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Organization	Clarkson University

Technical Section

Technical Objectives

The technical objective of this project is the development and evaluation of various digital signal processing (DSP) algorithms that will enhance hybrid lidar performance. Practical algorithms must be developed taking into account the underwater propagation channel and the processing requirements for each algorithm as shown in Figure 1.

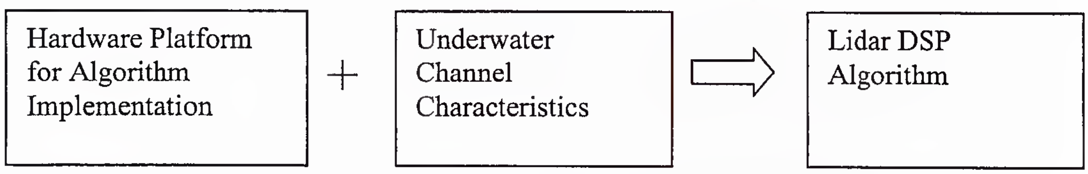


Figure 1. The development of lidar DSP algorithms must take into account hardware implementation and underwater channel characteristics.

Technical Approach

A significant challenge in hybrid lidar-radar is optical absorption and scattering. The absorption of the light photons by the molecules in the water channel contributes to a decrease in the total signal level collected at the receiver. This unwanted phenomenon can be reduced by selecting the wavelength of the laser light to be in the blue-green region. Backscattering occurs when transmitted light signal reflects off a water particulate and reaches the detector without first reaching the object. Thus, backscattered light contains no information regarding the object and it reduces the image contrast and resolution as well as the object ranging measurement accuracy. There have been various methods that attempt to reduce the backscatter. One method is to increase the modulation frequency beyond 100MHz and another is to use a dual high-frequency (>100MHz) approach that uses high speed modulation to help suppress backscatter while also providing an unambiguous range measurement. In general, it is desired to determine which combination of Radio Frequency (RF) modulation frequencies, modulation waveforms, and signal processing algorithms help improve hybrid lidar-radar performance in a variety of underwater environments.

The approach is to focus on the optical proximity detector that is being developed with ONR funding. The goal is to replace analog hardware with digital components to benefit from the advantages offered with digital hardware and signal processing, including better sensitivity due to large dynamic range digitizers and lossless digital demodulation and filtering, reconfigurability via software to improve sensor investigations have been performed to assess tradeoffs between dwell time and bandwidth compared to detection performance, indicating that dwell time and bandwidth can be reduced by 75% at a cost of less than 15% reduction in ranging performance. In summary, all techniques developed under this program have shown significant performance improvement potential in simulations and in laboratory-scale experiments.

Progress

Background

Hybrid lidar-radar ranging systems experience two main challenges from operating in the underwater channel that degrade system performance, as shown in Figure 1. The first of these is absorption, which occurs when a photon emitted from the laser is absorbed by water molecules or dissolved materials. Absorption causes the received signal level to decrease. The use of blue wavelengths in open ocean or green wavelengths in coastal ocean can be used to minimize absorption. The second challenge occurs due to scattering, in which photons are deflected out from the collimated laser beam after colliding with particles in the channel. Scattering degrades resolution and reduces range accuracy. Particularly challenging in the ranging application is the concept of backscattered photons, which are scattered backwards into the receiver field of view without reaching the desired object. If a sufficiently large amount of backscattered photons are collected, this may significantly reduce the probability of detection and increase the probability of false alarms. Scattering has typically been mitigated by applying high modulation frequencies to the laser as backscatter has been shown to have a lowpass frequency response [1,2]. In terms of backscatter reduction, ***this work applied digital signal processing algorithms to improve performance by processing the received signal rather than depending solely on the physics of the underwater channel.***

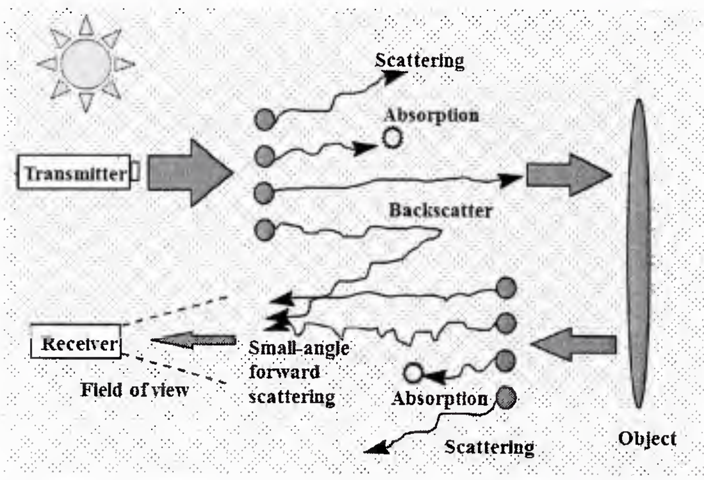


Figure 1. Sketch of water channel effects on hybrid lidar radar system

Although absorption and scattering are two separate physical phenomena, their effects on water conditions are often combined together into a single parameter, the attenuation coefficient c, which has units of m^{-1}. Beam attenuation in water follows an exponential decay law

$$P(c,z) = P_0 e^{-cz}$$

where z is the distance to the object and P_0 is the transmitted signal power. The product cz in the exponent is referred to as the number of attenuation lengths (a.l.), which is a dimensionless parameter used to compare ranging performance in different water conditions and at different distances.

between measurements without potentially substantial deviations caused by the system drifting in the water. For systems in deep waters, the system will not be able to receiver GPS due to the attenuation of the GPS signal by the water. A submerged platform with two photodetectors at an appropriate spacing avoids this issue but introduces new challenges associated with detector placement. For example, a system with two photodetectors should ideally place the detectors on an adjustable track so that the system could adapt the detector spacing to changes in modulation frequency or water conditions.

Experimental verification of this technique has been published in [4, 5]. In this work the delay line canceler was used with the single- and dual-tone approaches and experiments were performed in a 3.6 m long test tank at Patuxent River Naval Air Station. Results from these experiments are summarized in Table 3, which indicates performance in terms of attenuation lengths. In [7], experiments were performed with the delay line canceler applied to a single-tone system at 160 MHz, extending performance from 5.6 attenuation lengths out to 7.2 attenuation lengths. Experiments in [5] applied the delay line canceler to the dual frequency CW approach by applying a spatial filter independently to each modulation frequencies. Without applying the spatial filter, targets were detected out to approximately 5.7 attenuation lengths, while the spatial filter/dual frequency combination extended ranging performance out to 8.9 attenuation lengths. These results show that the spatial filter extends operating range by approximately 2-3 attenuation lengths by suppressing the backscatter return.

Table 3. Experimental Results using Delay Line Canceler

Technique	Attenuation lengths
Single-tone at 160 MHz	5.6
Delay line canceler at 160 MHz	7.2
Dual-tone at 140, 160 MHz	5.7
Delay line canceler at 140, 160 MHz	8.9

Approach #2: FDR – A New LIDAR Ranging Approach

In FY13, we adapted a technique from the fiber optic community known as frequency-domain reflectometry in order to overcome the unambiguous range and range precision tradeoffs affecting the dual-tone approach. The technique was adapted for underwater hybrid lidar-radar and simulations were performed in FY13. Simulations indicated a potential for centimeter-order accuracy and extended unambiguous ranging [6]. Experimental validation was obtained in FY14. The experimental setup and processing will be summarized before the results are presented.

The FY14 FDR experiments were performed in the 3.6 m tank at Patuxent River Naval Air Station, with results published in [7]. The experimental setup used to test the dual frequency and FDR ranging approaches is shown in Figure 2**Error! Reference source not found.**, with a photo of the setup shown in Figure 3**Error! Reference source not found.**. The output from a RF signal generator is combined with a DC source to modulate the current of a 442 nm laser diode. Modulated light was transmitted through a window onto a diffuse reflector target mounted on a translation stage. The target was moved in 10 cm increments from a range of 1.35 m to 3.05 m. The photomultiplier tube (PMT) collected light scattered from the submerged target through the window. A bias-tee at the output of the PMT separated the DC and AC components of the photocurrent. The DC-coupled signal was monitored on a multimeter to ensure that the PMT remained within its linear operating region. The AC-coupled signal was demodulated and digitized in the software defined radio (SDR) receiver. The I (in-phase) and Q (quadrature) samples obtained by the SDR were transferred over an Ethernet cable to a PC, where the data are processed in a custom LabVIEW program.

Figure 4. The FDR approach uses stepped frequency modulation and common DSP algorithms to compute range to an object.

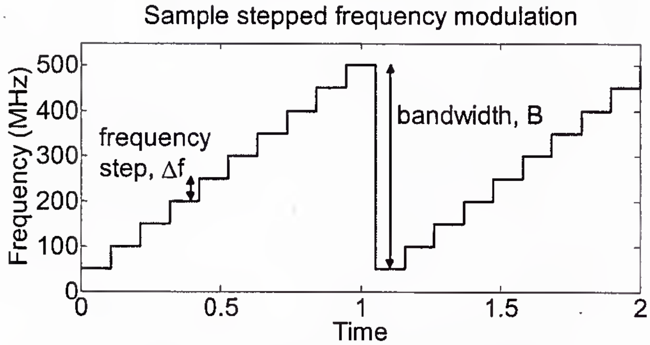


Figure 5. Sample stepped modulation

Ranging results from the FY14 FDR experiments and RangeFinder simulations are shown in Figure 6. The FDR configuration divided a 500 MHz bandwidth from 50 to 550 MHz into 128 equally spaced tones. A 400 MHz single frequency tone was used to enhance the range accuracy by smoothing out the "quantized range" calculated by FDR alone. In general, there is strong agreement between the simulated and experimental results. The simulated results suggest performance out to 10.8 attenuation lengths, while the experimental measurements obtained performance out to 10.2 attenuation lengths. The results can be qualitatively separated into two regions. In the first region, the FDR algorithm computes the range with range errors on the order of 3 cm. In the second region, beyond 10.2 attenuation lengths in the experimental data, the algorithm is no longer able to detect the target and instead returns the position of the backscatter. The observed sharp transitions are due to the peak detection algorithm being used in this work: when the target amplitude is less than the backscatter amplitude, the detection algorithm detects the center of the scattering region instead of the target. *However, it should be noted that the target is still evident in the range data even though it's amplitude drops below the backscatter amplitude. Therefore, additional performance is possible using a more sophisticated target detection algorithm.* To summarize, the FDR algorithm allows ranging out to 10.2 attenuation lengths, almost doubling the detection range previously achieved with the single- and dual-tone approaches.

marked on each profile in the three cases. In the object-limited case *(a)*, both FDR and FDR/BSS can easily detect the target position. In *(b)*, the turbidity has increased and a clutter return is now observed at short distances on the FDR range profile. Both algorithms are still able to detect the target position, with the clutter greatly reduced for FDR/BSS. Finally, in *(c)*, the turbidity is high enough that the FDR return is completely dominated by the clutter return. However, the FDR/BSS technique suppresses the backscatter enough that the target position can be detected in this scenario. This illustrates the capability for FDR/BSS to detect targets in what would otherwise be scatter-limited scenarios.

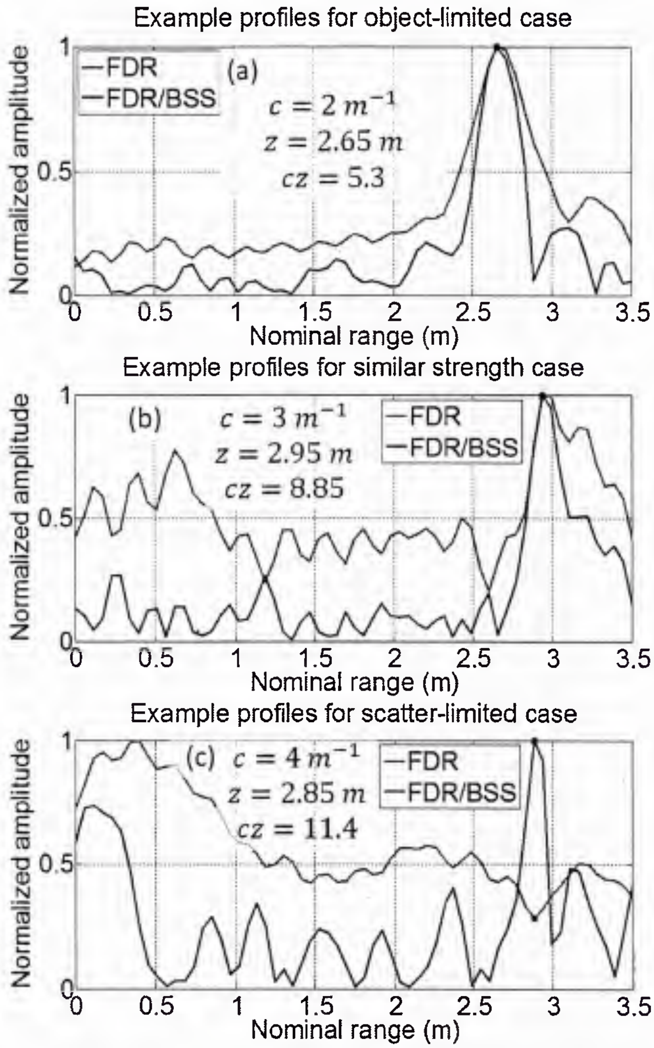


Figure 8. Range profiles for FDR/BSS and FDR algorithms for *(a)* object-limited, *(b)* similar strength, and *(c)* scatter-limited scenarios illustrating ability of FDR/BSS to suppress backscatter.

Simulated and experiment ranging results are shown below in Figure 9. In this case, the experimental results showed object tracking out to 14.7 attenuation lengths downrange, while the simulation predicts some degree of performance out to at least 18 attenuation lengths. In terms of range error, the mean range error in the object-tracking region of the experimental data is typically less than 3 cm. This indicates that FDR/BSS maintained comparable range error performance to FDR alone while extending the operating range by almost 5 attenuation lengths. As a result of the ability to suppress backscatter, FDR/BSS has a detection range almost three times as large as the single- and dual-tone approaches.

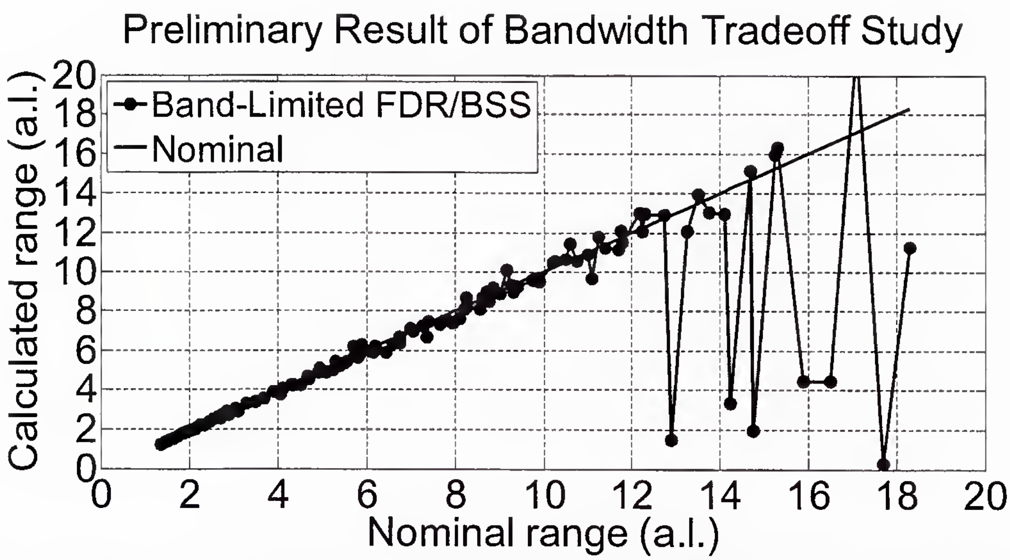


Figure 10. Tradeoff study configuration. A 75% reduction in bandwidth and sweep time resulted in a 14% reduction in ranging performance

Real-Time Digital Signal Processing

The second objective of this project is to deploy these ranging algorithms onto real-time digital signal processing (DSP) systems. Progress is summarized below in Table 4, where an X represents a completed task and the empty cells indicate remaining work. At this point the background information for each technique has been developed and large-scale tank experiments been performed for each technique. Real-time experiments have been performed for the single-tone, dual-tone, and FDR techniques with two different systems. A LabVIEW-based system at Patuxent River Naval Air Station has been used to perform real-time experiments for the single-tone and dual-tone techniques. This system uses the Ettus USRP (Universal Software Radio Peripheral) to perform pre-processing steps on raw data, with a PC running LabVIEW performing the final calculations to obtain range measurements.

A MATLAB-based system developed at Clarkson University in FY14 has been used to perform real-time FDR ranging experiments, as well as imaging experiments. The Clarkson experimental setup is shown below in Figure 11. A PC running MATLAB configures an RF signal generator to modulate a laser diode, which illuminates a target in a test tank. A PMT collects light reflected from the target. The AC component of the PMT output signal is mixed with a known reference signal, with the mixer output digitized. A DAQ (data acquisition) board is used to send the data to the PC, where range is calculated in the MATLAB program. This experimental setup can also be used to perform imaging experiments, in which an Arduino microcontroller board is used to control a laser scanner. A MATLAB program collects data at each pixel and constructs both amplitude and range images.

Table 4. Summary status of ranging algorithms

		Single-tone	Dual-tone	FDR	Single-tone + spatial filter	Dual-tone + spatial filter	FDR/ BSS
Background	Theory	X	X	X	X	X	X
	Simulation	X	X	X	X	X	X
Experimental	Proof-of-concept	X	X	X	X	X	X

In scenarios where the FDR sweep is unable to achieve the desired precision due to bandwidth limitations, an optional fifth step can be performed in which a single modulation frequency CW approach may be used to obtain finer precision ranging information following the peak detection step. Work is on-going to quantify the effects of reduced bandwidth and sweep time on ranging performance.

Project Summary

Several digital signal processing techniques to enhance the performance of underwater hybrid lidar-radar ranging systems have been developed and validated under this project. Results obtained with each technique are summarized below in Table 5, which also indicates theoretical ranging performance in open ocean and harbor waters for each technique. The first two entries of Table 5 are the baseline single-tone and dual-tone approaches that were previously developed by the Navy. The remaining table entries summarize the techniques developed under this program. The developed techniques have enhanced the ability to separate the target and backscatter components of underwater lidar return signals, enabling targets to be detected at increasingly longer distances. The experimental and simulated results show that thFDR/BSS approach can increase the ranging distance by a factor of ~2.6 compared to the single-tone approach. *However, it should be noted that additional FDR/BSS performance may be possible using a more sophisticated target detection algorithm since the target is still evident in the range data – the current peak detection algorithm simply detects the highest peak. Therefore, once the target amplitude drops below the volumetric backscatter amplitude the peak detection algorithm declares the volumetric backscatter to be the target.* Significant progress has been made in developing a digital signal processing approach to enable hybrid lidar-radar ranging systems to perform accurate automatic target detection at extended ranges.

Table 5. Summary of Range Performance*

Processing Technique	Attenuation lengths	Open ocean (m)	Harbor Conditions (m)	Average Range Improvement Factor
Single-tone (baseline)	5.6	56	2.8	1.00
Dual-tone (baseline)	5.7	57	2.9	1.03
Single-tone with spatial filter	7.2	72	3.6	1.29
Dual-tone with spatial filter	8.9	89	4.5	1.60
FDR	10.2	102	5.1	1.82
FDR/BSS	14.7	147	7.4	2.63

*Performance in real waters may vary from test tank results.

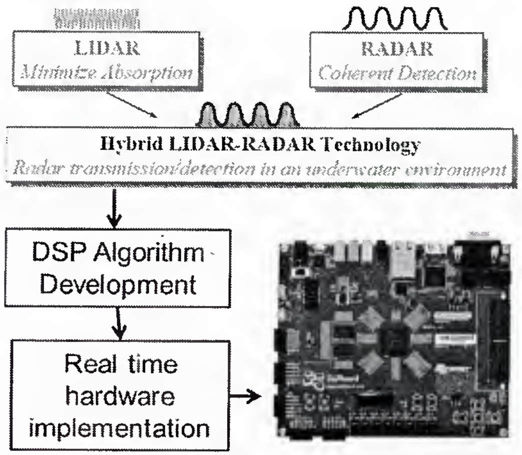
References

1. Mullen L.J., A.J.C. Vieira, and P.R. Herczfeld. "Application of RADAR technology to aerial LIDAR systems for enhancement of shallow underwater target detection," *IEEE Trans. Microw. Theory Techn.*, vol 43, pp. 2370-2377 (1995).
2. Pellen F., X. Intes, P. Olivard, Y. Guern, J. Cariou, and J. Lotrian. "Determine of sea-water cut-off frequency by backscattering transfer function measurement," *J. Phys. D: Appl. Phys*, vol. 33, pp. 349-354 (2000).

Advanced Digital Signal Processing for Hybrid Lidar N000141110371

Objective:

- Develop and evaluate various digital signal processing (DSP) algorithms that will enhance hybrid lidar performance.



Approach:

- Account for both practical hardware implementation and realistic underwater propagation characteristics
- Leverage existing Navy proximity detection work
- Use a combination of simulated and experimental lidar data to validate algorithms
- Leverage mature signal processing techniques developed for radar and communications to the maximum extent possible

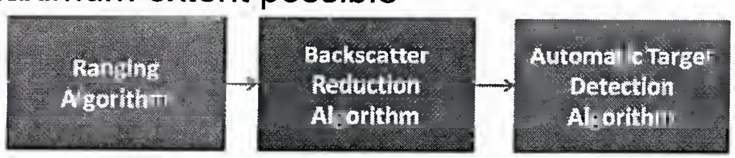
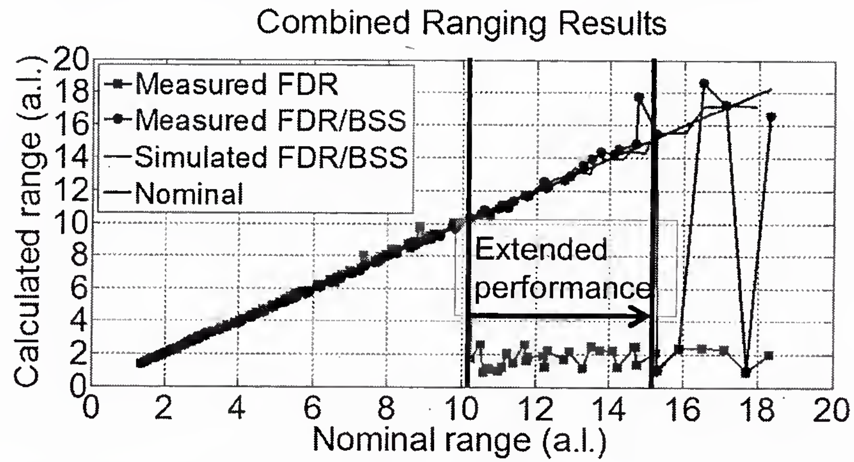


Figure: A new FDR/BSS ranging and backscatter reduction technique was developed that can reduce backscatter by 10dB to extend ranging performance to ~ 15 attenuation lengths.



Scientific or Naval Impact/ Results:

- Three new lidar signal processing approaches investigated
- Significant performance improvements validated via simulation and laboratory-scale experiments
- Detection range more than doubled relative to previous processing techniques

Processing Technique	Attenuation lengths	Open-ocean (m)	Harbor Conditions (m)	Average Range Improvement Factor
Single-tone (baseline)	5.6	56	2.8	1.00
Dual-tone (baseline)	5.7	57	2.9	1.03
Single-tone with spatial filter	7.2	72	3.6	1.29
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FDR/BSS	14.7	147	7.4	2.63